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Barakat, A., Thian, M., & Fusco, V. (2015). *Towards generalized Doherty power amplifier design for multiband operation*. Paper presented at International Microwave and Optoelectronics Conference (IMOC 2015), Porto de Galinhas/Pernambuco, Brazil. <http://www.imoc2015.com/>

**Document Version:**  
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# Towards Generalized Doherty Power Amplifier Design for Wideband Multimode Operation

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**Abstract**—This paper presents a new variant of broadband Doherty power amplifier that employs a novel output combiner. A new parameter  $\alpha$  is introduced to permit a generalized analysis of the recently reported Parallel Doherty power amplifier (PDPA), and hence offer design flexibility. The circuit prototype of the new DPA fabricated using GaN devices exhibits maximum drain efficiency of 85% at 43-dBm peak power and 63% at 6-dB back-off power (BOP). Measured drain efficiency of >60% at peak power across 500-MHz frequency range and >50% at 6-dB BOP across 480-MHz frequency range were achieved, confirming the theoretical wideband characteristics of the new DPA.

**Keywords**—Broadband; combiner; Doherty; GaN HEMT; load modulation; multiband; power amplifier; transmission line.

## I. INTRODUCTION

In Doherty power amplifier (DPA) design, the output combining network plays a pivotal role in facilitating load modulation through which high efficiency can be obtained not only at peak output power but also at back-off powers (BOPs). The conventional DPA (CDPA) architecture, Fig. 1(a), proposed in [1] is effective for single frequency band operations whereas recent research efforts [2]–[7] have focused on developing output combiners that are suited for multiband operations. Demonstrated in [2], the output combiner of the parallel DPA (PDPA) has capability to improve the bandwidth of the CDPA at BOP. This is achieved by reducing the transformation ratio of  $Z_T$  (the quarter-wave line at the Carrier PA output) by a factor of two, hence decreasing the loaded quality factor. However, two impedance transformer networks (ITNs), one at the Carrier path and one at the Peaking path, were required to match the standard output combining network system impedance (50  $\Omega$ ) to the nominal Class-E load resistance (25  $\Omega$ ) at peak power. Furthermore, the design procedures described in [2] require nonlinear optimization (tuning) of  $Z_T$  and  $Z_{TA}$  in order to obtain best achievable efficiency over an intended operating bandwidth.

In this paper, a new parameter  $\alpha$  is first introduced to permit the analysis of generalized PDPA, termed here as Generalized DPA (GDPA); Fig. 1(b). The optimum value of  $\alpha$  that would give best wideband performance is then determined. From the analysis, it turns out that  $\alpha_{opt} = 0.5$  compared to  $1/\sqrt{2}$  used in PDPA. Broader bandwidth performance achieved for  $\alpha = 0.5$  is due to the fact that (i) the transformation ratio of  $Z_T$  at BOP is reduced by a factor of four with respect to CDPA or by a factor of two with respect to PDPA and (ii)  $Z_2$

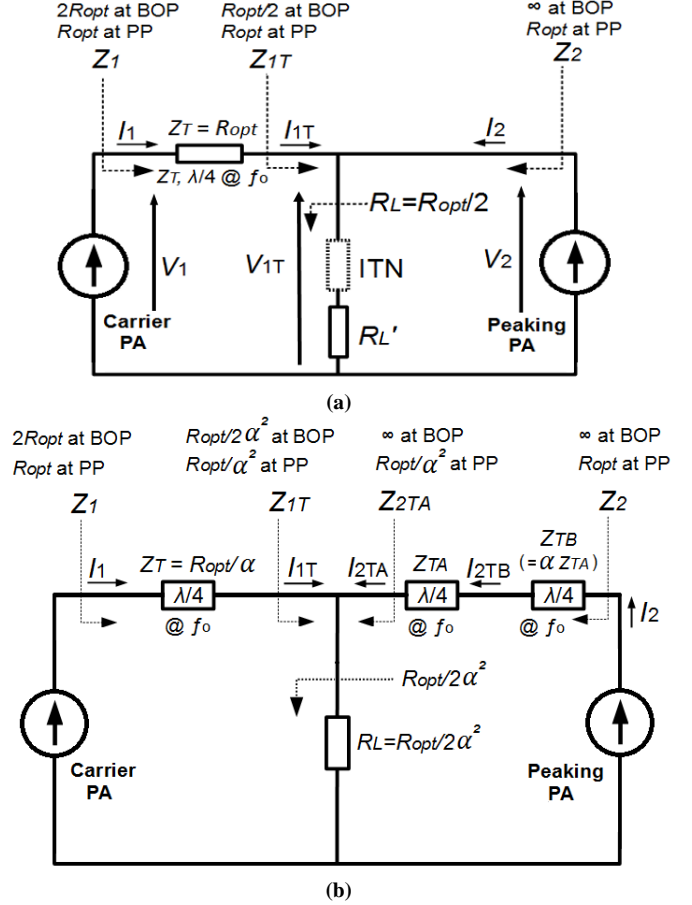


Fig. 1. DPA architectures: (a) Conventional DPA (CDPA) and (b) proposed Generalized DPA (GDPA).

variation with frequency at peak power is minimized. Importantly, the new analysis allows the output combining network system impedance to be matched directly to the nominal Class-E load resistance at peak power, thereby dispensing the need for the aforementioned two ITNs.

## II. OPERATING PRINCIPLE OF GENERALIZED DOHERTY POWER AMPLIFIER (GDPA)

Suppose two identical switch-mode PAs (such as Class E) are used as the Carrier and Peaking PAs and the optimum resistance required by these PAs to achieve maximum efficiency at peak power is  $R_{opt}$ . At 6-dB BOP, the Peaking PA is still turned off and the optimum resistance of the Carrier PA

must be set to  $2R_{opt}$  in order to satisfy the Doherty load modulation requirement.

The structure of the proposed GDPA is compared with the CDPA in Fig. 1. In CDPA, the combined impedance presented by the Peaking and Carrier branches ( $R_L$ ) is fixed i.e.  $R_{opt}/2$ . An ITN is typically required at the output to transform  $R_L = R_{opt}/2$  into the standard load impedance of  $50 \Omega$  ( $R_L'$ ). To obtain a broadband performance, this ITN must comprise of multi-section quarter-wave lines resulting in increased circuit complexity and large physical size. In GDPA, two transmission lines ( $Z_{TA}$  and  $Z_{TB}$ ) are added at the Peaking side. A  $90^\circ$  delay transmission line is inserted at the input of the Carrier PA so as to ensure the phase of the signal in the Carrier PA path match the phase of the signal in the Peaking PA path prior to them being combined. The operating principles of GDPA are explained as follows:

a) *Analysis at back-off power*

At 6-dB BOP, the Carrier PA is ON while the Peaking PA is still OFF. Since the Peaking PA current is zero, the impedance  $Z_2$  is infinity. Owing to two quarter-wave lines  $Z_{TA}$  and  $Z_{TB}$ , the impedance  $Z_{2TA}$  is also infinity. At the Carrier side,  $Z_1$  must be set to  $2R_{opt}$  to allow maximum efficiency at 6-dB BOP and hence  $Z_{1T}$  can be calculated as (1). Since  $Z_{2TA} = \infty$ , the load resistance  $R_L$  is simply equal to  $Z_{1T}$ .

$$Z_{1T} = \frac{Z_T^2}{Z_1} = \frac{Z_T^2}{2R_{opt}} = R_L \quad (1)$$

b) *Analysis at peak power*

At peak power, both Carrier and Peaking PAs are ON. As shown in (2a) and (2b), the magnitudes of the Carrier and Peaking currents ( $I_{1T}$  and  $I_{2TA}$ ) must be equal so as the parallel combination of  $Z_{1T}$  and  $Z_{2TA}$  can be directly matched to  $R_L$ .

$$Z_{1T} = R_L \left( 1 + \frac{I_{2TA}}{I_{1T}} \right) = 2R_L \quad (2a)$$

$$Z_{2TA} = R_L \left( 1 + \frac{I_{1T}}{I_{2TA}} \right) = 2R_L \quad (2b)$$

$Z_1$  and  $Z_2$  must be set to  $R_{opt}$  to allow maximum efficiency at peak power and therefore

$$Z_1 = \frac{Z_T^2}{Z_{1T}} = R_{opt} \quad (3a)$$

$$Z_2 = \frac{Z_{TB}^2}{Z_{TA}^2} Z_{2TA} = R_{opt} \quad (3b)$$

Substitution (2a) into (3a) results in

$$Z_T^2 = 2 R_{opt} R_L \quad (4)$$

Substitution (2b) into (3b) results in

$$\frac{Z_{TB}^2}{Z_{TA}^2} = \frac{R_{opt}}{2R_L} \quad (5)$$

From (4) and (5), we can obtain the following relationship

TABLE I  
OUTPUT COMBINER PARAMETERS

	GDPA	BB GDPA	PDPA	CDPA
$\alpha$	$0 < \alpha < \infty$	0.5	$\frac{1}{\sqrt{2}}$	1
$Z_T$	$\frac{R_{opt}}{\alpha}$	$2R_{opt}$	$\sqrt{2}R_{opt}$	$R_{opt}$
$R_L$	$\frac{R_{opt}}{2\alpha^2}$	$2R_{opt}$	$R_{opt}$	$\frac{R_{opt}}{2}$
$\frac{Z_{TB}}{Z_{TA}}$	$\alpha$	0.5	$\frac{1}{\sqrt{2}}$	-

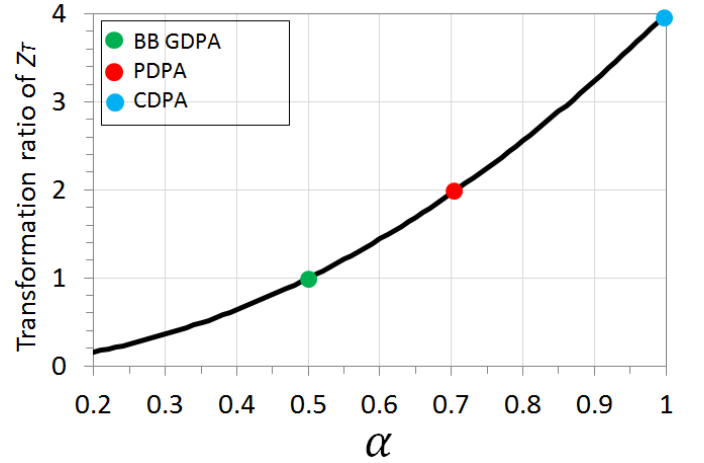


Fig. 2. The relationship between the transformation ratio of  $Z_T$  and  $\alpha$  at 6-dB BOP. An ultimate broadband performance is achieved when the ratio is unity.

$$\frac{Z_{TB}}{Z_{TA}} = \frac{Z_T}{2R_L} = \alpha \quad (6)$$

Note that  $\alpha$  in (6) is constant. The component values of the GDPA can then be derived using (4)-(6) as follows:

$$Z_{TB} = \alpha Z_{TA} \quad (7)$$

$$Z_T = \frac{R_{opt}}{\alpha} \quad (8)$$

$$R_L = \frac{R_{opt}}{2\alpha^2} \quad (9)$$

Table I shows a comparison between GDPA, PDPA, and CDPA output combiner parameters, from which it can be seen that when  $\alpha = 1/\sqrt{2}$  GDPA is reduced to PDPA and when  $\alpha = 1$  GDPA is reduced to CDPA, implying that PDPA and CDPA are essentially a subset of GDPA. The operational bandwidth can be extended by properly selecting the value of  $\alpha$ . For instance, if  $\alpha$  is set to 0.5 rather than 1 as in CDPA, the transformation ratio of  $Z_T$  at the 6-dB BOP will be reduced by a factor of four (Fig. 2). Fig. 3 shows the effect of frequency variation on  $Z_2$ . As the operating frequency moves away from the centre frequency, the magnitude of  $Z_2$  deviates from its optimal value i.e.  $R_{opt}$ . It can be observed that  $|Z_2|$  variation with frequency is minimal when  $\alpha = 0.5$ .

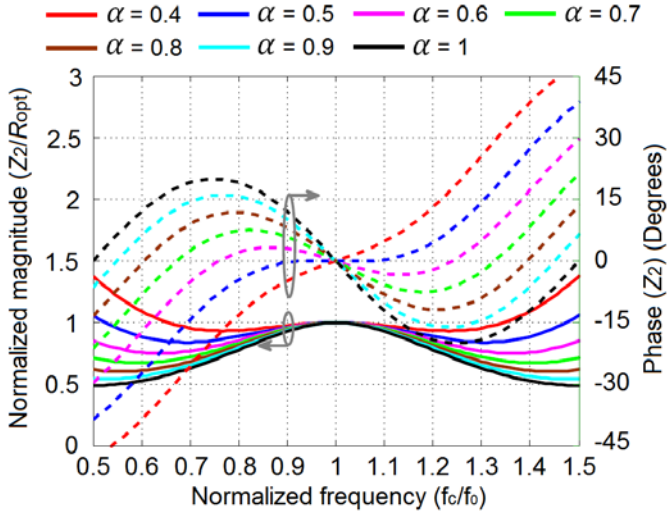


Fig. 3. Theoretical magnitude (solid lines) and phase (dashed lines) of  $Z_2$  at peak power for  $\alpha$  from 0.4 to 1. The BB GDPA ( $\alpha = 0.5$ ) has smaller impedance variation than the PDPA ( $\alpha = 0.7$ ) within the intended normalized bandwidth from 0.875 to 1.125.

### III. BROADBAND GDPA DESIGN METHODOLOGY

An example is given here to illustrate step-by-step design procedures of GDPA. Given  $R_L = 50 \Omega$ ,  $R_{opt} = 25 \Omega$ , and operating frequency = 2.1-2.6 GHz (corresponds to 21% fractional bandwidth), the output combiner can be designed as follows:

*Step 1: Calculate  $\alpha$  using (9)*

$$\alpha = \sqrt{\frac{R_{opt}}{2R_L}} = 0.5$$

This value gives a unity transformation ratio of  $Z_T$  at the 6-dB BOP, resulting in an ultimate broadband performance. In addition, this will enhance the impedance matching of  $Z_2$  to  $R_{opt}$  and increase the efficiency at peak power level.

*Step 2: Calculate  $Z_T$  using (8)*

$$Z_T = \frac{R_{opt}}{\alpha} = 50 \Omega.$$

*Step 3: Determine  $Z_{TA}$  and  $Z_{TB}$*

The value of  $Z_{TA}$  is obtained through an optimization using CAD tool to give minimal  $Z_2$  variation with frequency (Fig. 4). Subsequently, the value of  $Z_{TB}$  can be computed using (7).

$$Z_{TA} = 70 \Omega.$$

$$Z_{TB} = \alpha Z_{TA} = 35 \Omega.$$

Fig. 5 shows the final values of the output combiner parameters.

### IV. CIRCUIT IMPLEMENTATION AND MEASUREMENT

A circuit prototype was realized on Rogers RO4350B substrate that has a thickness of 0.508 mm, a dielectric constant of 3.66, and a loss tangent of 0.0037. A hybrid coupler 11306-3S from Anaren was used to provide two equal input powers to

the Carrier and Peaking PAs as well as a  $90^\circ$  phase shift at the input of the Carrier amplifier. As a result, the  $90^\circ$  delay transmission line depicted in Fig. 1(b) is no longer required. The broadband Class-E PA employing reactance compensation technique reported in [2] was used for both cells. Two CGH40010F GaN HEMTs from Cree were used with drain-source voltage  $V_{DC} = 28 \text{ V}$  and gate voltages  $V_{gC} = -2.7 \text{ V}$  and  $V_{gP} = -4.75 \text{ V}$ . Figs. 6 and 7 show the fabricated circuit prototype and measurement setup.

Characterizations using continuous wave (CW) input signal were carried out across 2.1-2.6 GHz frequency range at peak power (36-dBm input power) as well as back-off power (27.5-dBm input power). Measured output power, gain and drain efficiency at peak power level are plotted against frequency in Fig. 8. A maximum drain efficiency of 85.3% is obtained at 2.34 GHz. The Doherty PA exhibits a broadband performance, achieving a drain efficiency  $>70\%$  within 380-MHz frequency range (2.18-2.56 GHz), and  $>60\%$  within 500-MHz frequency range (2.1-2.6 GHz). The PA delivered  $43 \pm 2 \text{ dBm}$  peak output power over the entire bandwidth.

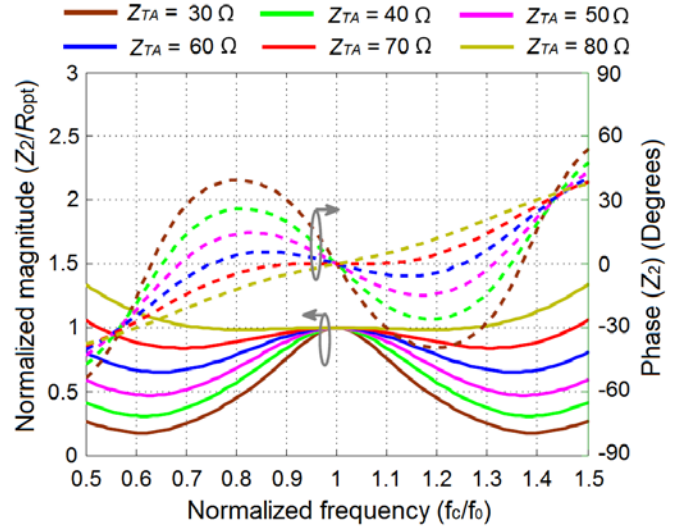


Fig. 4. The normalized magnitude  $Z_2/R_{opt}$  and phase of  $Z_2$  versus normalized frequency (Carrier frequency/Center frequency) at peak power level.  $Z_{TA}$  is varied from 30 to 80  $\Omega$ ,  $\alpha = 0.5$  and  $R_L = 50 \Omega$ .

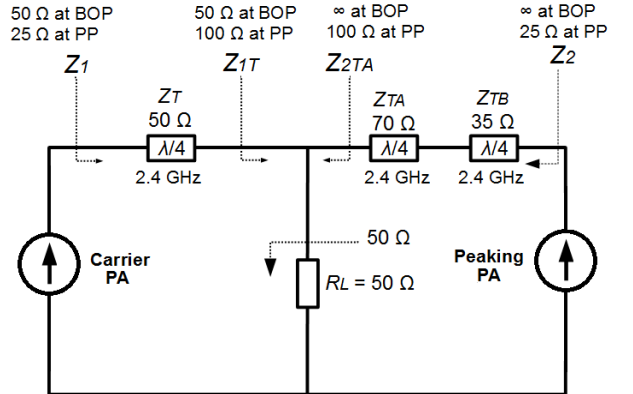


Fig. 5. The final design of the proposed BB GDPA output combiner, showing the load modulation process.



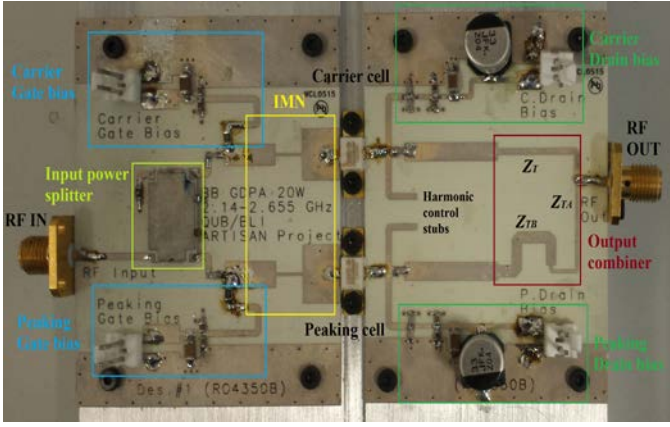


Fig. 6. The fabricated circuit prototype of the BB GDPA, measures  $10 \times 6.2 \text{ cm}^2$ .

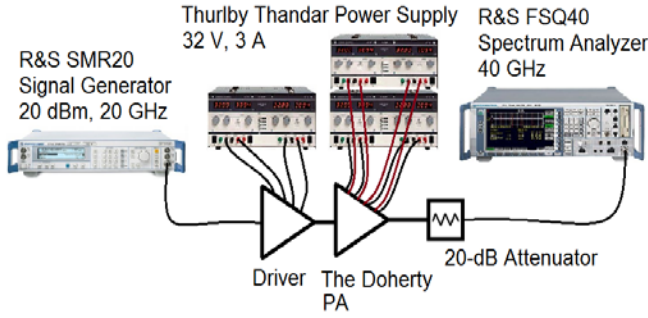


Fig. 7. Measurement setup.

The circuit performance at 6-dB BOP level is depicted in Fig. 9. A maximum drain efficiency of 63% is observed at 2.22 GHz. The drain efficiency is  $>50\%$  across 480-MHz bandwidth (2.12-2.6 GHz). Shown in Fig. 10 is the PA performance against output power in the 2.11-2.17 GHz UMTS band. A maximum drain efficiency of 68% and 63% were achieved at peak power (45 dBm) and at 6-dB output BOP, respectively. The performance of the proposed GDPA is summarized and compared with other wideband DPAs in Table II. At both peak power and 6-dB BOP, the new GDPA exhibits highest maximum drain efficiency.

## V. CONCLUSION

A generalized analysis of the recently reported PDPA has been described through introduction of parameter  $\alpha$ . This results in a new variant of DPA with enhanced bandwidth characteristics, termed as GDPA. Design procedures are given to calculate the output combiner parameters of the GDPA. A circuit prototype was realized using GaN HEMTs to deliver a peak power around 43 dBm. Measurements have shown a broadband performance wherein the drain efficiencies at peak power and 6-dB BOP were, respectively,  $>60\%$  within 500-MHz frequency range and  $>50\%$  within 480-MHz frequency range. The compact size and high efficiency performance over a wide bandwidth for this design can introduce it as a good candidate for multiband 2.1-2.6 GHz LTE micro-cell base stations and active antenna array systems.

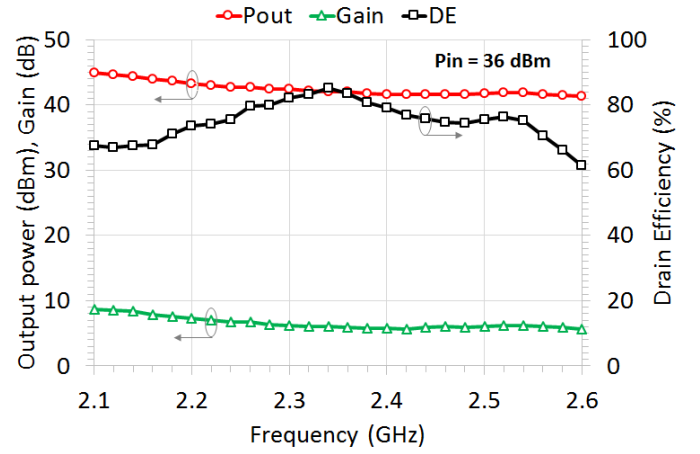


Fig. 8. Measured output power, gain and drain efficiency at peak power, versus frequency.

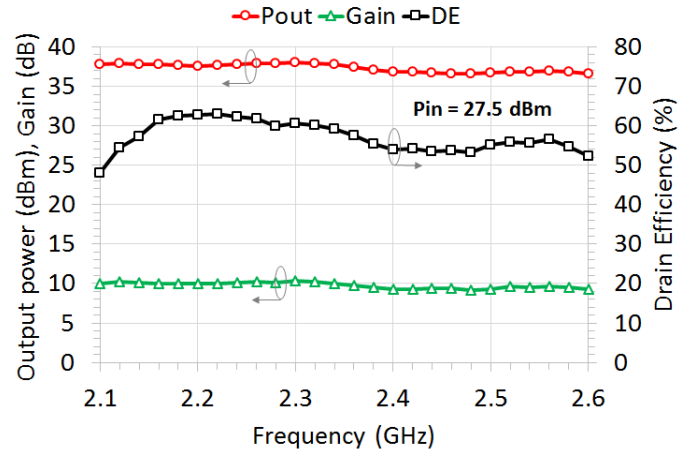


Fig. 9. Measured output power, gain and drain efficiency at 6-dB BOP versus frequency.

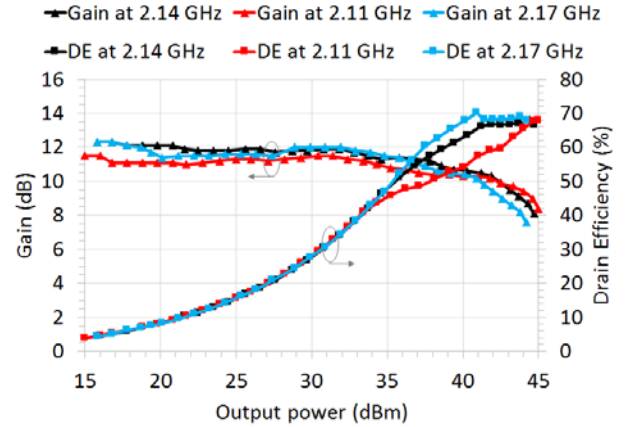


Fig. 10. Measured gain and drain efficiency versus output power.

## ACKNOWLEDGMENT

The authors wish to thank Florian Pivitt, Senad Bulja, Ray Kearney (Bell Labs Ireland), Jim Knox and Gerry Rafferty (Queen's University Belfast) for their contribution in this work.

TABLE II  
PERFORMANCE SUMMARY AND COMPARISON WITH OTHER PUBLISHED  
WIDEBAND GAN HEMT DPAS

Ref.	Freq. (GHz)	$P_{SAT}$ (dBm)	Peak power		6-dB BOP	
			Max/Min DE (%)	BW @ DE>70% (MHz)	Max/Min DE (%)	BW @ DE>50% (MHz)
[3]	1.7-2.3	53	72/58	160	61/41	240
[4]	1.7-2.4	41	72/53	150	59/43	140
[5]	1.96-2.46	42.2-44.2	66/52	0	53/40	110
[6]	0.75-0.95	48	64/56	0	64/52	200
[7]	0.73-0.98	42.7-44.6	67/40	0	61/43	230
<b>This work</b>	<b>2.1-2.6</b>	<b>43</b>	<b>85/61</b>	<b>380</b>	<b>63/48</b>	<b>480</b>

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